LANDSCAPE POSITION, SURFACE HYDRAULIC GRADIENTS AND EROSION PROCESSES

D. S. GABBARD[1], C. HUANG[1*], L. D. NORTON[1] AND G. C. STEINHARDT[2]

[1]*USDA-ARS National Soil Erosion Research Lab., 1196 SOIL Bldg, Purdue University, West Lafayette, IN 47907-1196, USA*
[2]*Agronomy Dept, 1150 LILY Bldg, Purdue University, West Lafayette, IN 47907-1150, USA*

Received 10 September 1996; Revised 20 March 1997; Accepted 29 April 1997

ABSTRACT

Different hydraulic gradients, especially due to seepage or drainage, at different locations on a hillslope profile may have a profound effect on the dominant erosion processes. A laboratory study was designed to simulate hillslope processes and quantify effects of surface hydraulic gradients on erosion for a Glynwood clay loam soil (fine, illitic, mesic Aquic Hapludalf). A 5 m long, 1·2 m wide soil pan was used at 5 and 10 per cent slopes with an external watering tube to vary the soil bed's hydrological conditions. Different combinations of slope steepness with seepage or drainage gradients were used to simulate the hydrologic conditions on a 5 m segment of a hillslope profile. Runoff samples were taken during rainfall-only and rainfall with added inflow. Results showed that, under drainage conditions, interrill processes dominated and rilling was limited. The surface contained scattered crescent-shaped pits after the run. Under seepage conditions, rilling processes dominated and the inflow introduced at the top of the soil pan further accelerated the headward erosion of the rills. Erosion rates increased by as much as 60 times under seepage conditions representative of the lower backslope when compared to drainage conditions that generally occur at the upper backslope. This indicated that rills and gullies on backslopes and footslopes may be catalysed or enhanced by seepage conditions rather than form from flow hydraulic shear stress alone. An understanding of spatial and temporal changes that affect both hillslope hydrology and erosional processes is needed to develop accurate process-based erosion prediction models. This knowledge may lead to different management practices on landscape positions where seepage occurs. © 1998 John Wiley & Sons, Ltd.

Earth surf. process. landforms, **23,** 83–93 (1998)
KEY WORDS: soil erosion; hillslope hydrology; seepage; drainage; hydraulic gradient

INTRODUCTION

Water movement on erosional landscapes, from both surface and subsurface sources, is the dominant mechanism in shaping landforms and the formation of soil mantle covering it (Birkeland, 1984; Ritter *et al.*, 1995). When subsurface flow exfiltrates onto the soil surface, the development of several different landscape features may evolve. Seepage cusps, concavities on shallow slopes serving as an area of deposition and vegetative growth, result from an increase in the downwearing of the backslope in the seepage zones. This increased erosion of the backslopes relative to the summits lead to the development of tors and the preservation of the crests (Bunting, 1961). Dunne (1990) showed that the initiation of scarp retreat could occur if soil and the underlying rock were predominantly non-cohesive in nature and susceptible to mass-wasting processes.

In soil mechanics literature, the effects of moisture condition on soil strength have been known for a long time. The Revised Coulomb Equation proposed by Terzaghi in the mid-1930s relates the shearing strength, s, to normal stress, σ, and pore-water pressure, u:

$$s = c + (\sigma - u)\ tan\ \phi$$

where c is cohesion and ϕ is the internal angle of friction (Terzaghi and Peck, 1967). The difference between normal stress and pore-water pressure, or $\sigma - u$, is called effective stress. The pore pressure provided the link between the normal and effective stress because the pore pressure can add to or substract from the normal stress to give the normal effective stress, depending on the location of the water table and movement of the water.

* Correspondence to: C. Huang

CCC 0197-9337/98/010083–11 $17.50

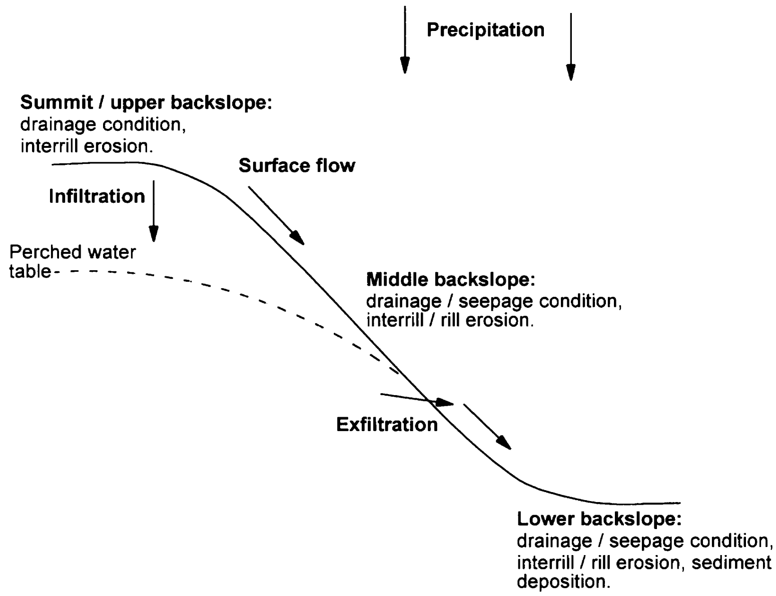


Figure 1. Hillslope position, hydrologic condition and erosion processes

Analyses of seepage as a force which counteracts the internal angle of friction were used to postulate sapping at the upper end of the seepage face and the subsequently induced mass failure causing headward erosion (Dunne, 1990). Detailed soil mechanical calculations by Iverson and Major (1986) and Howard and McLane (1988) on sand and non-cohesive materials showed that seepage caused a reduction of the effective stress in proportion to the hydraulic potential gradient, and may, when conditions are close to static liquefaction, catalyse debris flow. Although these studies used non-cohesive materials, the process of seepage-induced headward development also pertains to cohesive materials.

Despite the common knowledge of seepage effects on reducing soil strength and causing slope failure and headward erosion, very few studies have been conducted to measure seepage-induced erosion combined with rainfall events. Under simulated rainfall on a soil pan, Stolte *et al.* (1990) tested the effects of return flow (or seepage) on erosion from both a loam and sand and found seepage effects on sand but not on the loamy soil. They suggested that the low permeability of the loam soil prevented return flow from producing any measurable effect on erosion. A recent study by Huang and Laflen (1996) showed significant seepage effects on erosion for a clay loam soil under both simulated rainfall and concentrated flow conditions. Differences between the findings of these two studies probably resulted from the difference in time allowed for seepage to occur before their respective experiments were conducted.

This research is an extension of the study by Huang and Laflen (1996) on seepage effects to incorporate hydrologic conditions and processes occurring on a hillslope. It took a preliminary look at how slope, subsurface hydrology, raindrop impact, and surface flow conditions affect the erodibility of soil at different locations along a hillslope and how these different processes aid in the transport of soil particles from a hillslope component. A conceptual hillslope process model developed for this study is illustrated in Figure 1. It is hypothesized that different hillslope positions will have different hydrological conditions and, furthermore, these will affect erosion processes. For example, drainage conditions are predominant near the summit, shoulder and upper backslope areas. The small amount of surface flow contributed from the area upslope leads to interrill-dominated processes in the upper parts of the hillslope. Further downslope, the increased water from areas upslope enhances the concentration of surface flow, and hence rill erosion processes. Near the toe of the slope, seepage may occur during periods of excessive soil moisture. Sediment deposition is another significant process at this slope position.

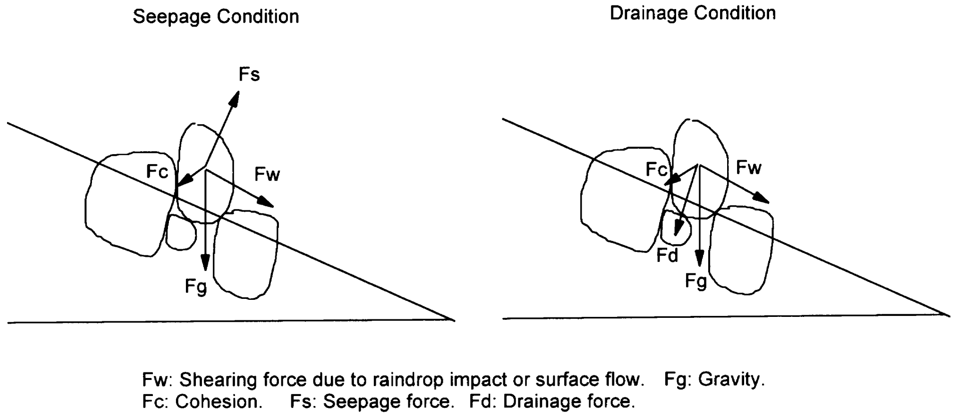


Figure 2. Force diagrams showing seepage and drainage effects

A simple force diagram to show how the seepage or drainage flow can change the stress on a soil aggregate at the surface is presented in Figure 2. Under drainage conditions, the additional suction from the downward flow holds down the aggregates in place, and thus increases the resistance for soil detachment. Seepage flow enhances the ‘quick’ condition as interparticle forces are reduced, and thus reduces the soil strength. Therefore, changes in the near-surface hydraulic gradient will affect the soil strength against erosive forces, or erodibility. These spatial and temporal changes of the hydrological conditions in field hillslopes and their effects on soil erodibility and processes of erosion were simulated in this laboratory experiment.

A 5 m long soil box was designed to recreate hydrologic conditions of a segment of the hillslope under various scenarios: subsurface water movement, slope steepness, raindrop impact and concentrated flow. Experiments were designed to quantify sediment delivery under different combinations of soil erodibility and flow erosivity representing processes occurring at different hillslope positions. Results of this study contribute to the understanding of erosion processes and their relationships to the spatially and temporally varying hydrologic conditions on a hillslope.

MATERIALS AND METHODS

Soil sample collection

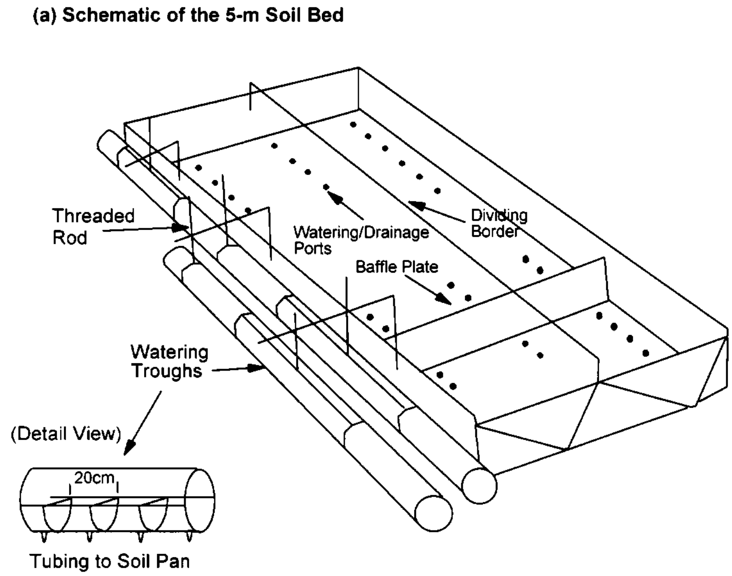
The soil used in this study was a Glynwood clay loam (fine, illitic, mesic Aquic Hapludalf with 22 per cent sand, 49 per cent silt and 29 per cent clay) collected from a farm in Blackford County, Indiana. Blackford County is an area of little relief with till plains and moraines comprising most of the present landforms. The soils are predominantly Wisconsian age clayey glacial till and farms in the surrounding areas are mostly row-cropped using various tillage practices.

The sampled field had been under a no-till management system for over nine years. Soil penetrometer readings made in the field showed a restrictive zone at an average depth of 25 cm. These measurements indicated the development of a less permeable compacted layer due to previous tillage practices or farm traffic following conversion to no-till.

Surface soil was collected, randomly to a depth of 10 cm, from the summit and upper portion of the convex shoulder on the hillslope. The soil was air-dried in the laboratory prior to the experiment. The soil was neither sieved nor ground and care was taken to preserve its original aggregation. After drying, the soil had a subangular-blocky structure.

Experimental setup

The study was conducted on a 5 m long, 1·2 m wide and 0·3 m deep soil box (Figure 3). The downslope end of the box was 5 cm lower than the other three sides with two 60 cm wide runoff collection troughs. The depth of



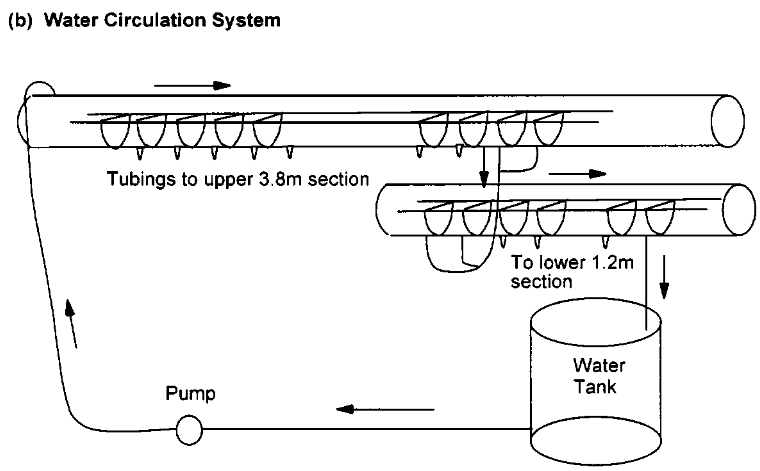


Figure 3. Design of the 5 m soil bed and the water circulation system

soil fill was approximately 25 cm with a 2 cm layer of sand at the bottom to promote bed saturation from the watering system. The bed was adjustable from 0 to 40 per cent slope in 5 per cent increments. Sheet metal plates were inserted 10 to 15 cm into the soil along the length of the soil bed to create two 0·6 m wide plots with equivalent subsurface hydrology. A baffle plate, attached and sealed to the bottom of the soil box, was placed 1·2 m from the downslope end of the box to force the subsurface flow to exfiltrate before the end of the plot in order to minimize box end effects.

The soil bed had 75 watering ports at the bottom. These ports were arranged in 25 rows, three ports per row, with 20 cm spacing between rows. A water circulation system was designed to supply water to the bottom of the soil box with a capability to maintain a constant water level of any position relative to the soil surface. The watering system (Figure 3) consisted of two PVC pipes attached externally from the soil bed. The positions of these two pipes were adjustable and could be set at any level independent of the soil bed, therefore causing seepage or drainage under tension. The PVC pipes had baffles inserted halfway through the tube at 20 cm spacing, which was identical to the row spacing between watering ports in the soil box. These baffles allowed

water to accumulate in individual reservoirs at atmospheric pressure and cascade sequentially over the baffles to fill the next reservoir. Each reservoir in the PVC pipe was connected, via flexible tubes, to a corresponding row of three water ports in the soil box. The watering system maintained a constant hydrostatic pressure at the bottom of the soil box. Excess water at the end of the PVC pipes was recirculated through the system.

Three programmable rainfall simulators (Foster *et al*., 1979), each with five nozzles at 1·07 m spacing, were placed 2·3 m above the soil bed. These rainfall simulators were centred over the bed and spaced 0·76 m apart. VeeJet nozzles (Part no. 80100, Spraying Systems Co., Wheaton, IL) were used and the nozzle pressure was kept at 6 psi. These nozzles were programmed to oscillate at a rate to produce 50 mm h^{-1} simulated rainfall. Rainfall distribution of this oscillating-nozzle-type simulator was quantified by Neibling *et al*. (1978).

Two inflow boxes were placed at the top end of the soil bed to allow the introduction of added inflows to the soil surface. These boxes were 0·6 m wide, 0·46 m deep and were levelled initially and periodically checked to ensure an equal distribution of added flow to each of the 0·6 m wide plots. Flow additions were made by overflowing these two inflow boxes. The flow rate was set by adjusting flow valves according to the reading from an in-line flow meter. The plumbing system was designed to supply at least 40 l min^{-1} of inflow to each inflow box. Deionized water was used throughout the experiment.

Soil box preparation

Preparation of the soil box included replacing eroded soil from the prior experimental tests with field-collected soil, breaking up clods to 3–4 cm sizes, and smoothing out the visual irregularities on the surface by hand or rake. Once the box was prepared, metal sheets were hammered into the middle of the bed to form two replicate plots, each 0·6 m wide and 5 m long. The box was then set to its level position and rained on for 30 min at 50 mm h^{-1} intensity. This initial rainstorm, as part of the soil box preparation procedure, was used to wet down the soil surface and to consolidate the loose aggregates to form a wet surface seal. The initial storm also reduced the variability from the surface preparation.

Hydraulic gradients were controlled by adjusting the position of the water tube relative to the soil. After the surface water from the initial 30 min 50 mm h^{-1} rain event had infiltrated, the soil box was set to the selected slope steepness and hydrological condition. The height of the watering tubes relative to the soil surface dictated the amount of hydrostatic pressure at the bottom of the soil pan. The watering system was applied continuously to maintain constant water levels in the supply troughs before and during the erosion study.

With only one soil box, different treatments had to be conducted sequentially. Treatment replications were sequenced using a random number generator. The treatments were water tube heights at 20 and 10 cm above the soil surface (20WT and 10WT), at the soil surface (0WT), 10 cm below the surface (–10WT) and no water tubes connected (NWT) for the 5 per cent slope gradient. The 20WT treatment was not used with 10 per cent slope. Each soil box was replicated at least twice to produce a minimum of four replications.

Under the three high water tube settings (20, 10 and 0 cm), water seeped out of the soil and flowed across the surface. The background seepage rates were measured before and after the erosion run.

Experimental procedure

The erosion study was conducted 24 h after the initial preparation rain. The run started with a 30 min rainstorm at 50 mm h^{-1}. During the rainstorm event, runoff samples were collected every 3 min. After the rainfall-only portion of the run, inflow was added while the run continued. A total of five levels of inflow (7·6, 15·1, 22·7, 30·2 and 37·8 l min^{-1}) were applied, starting with the lowest flow rate. Each level of inflow was applied for 8 min with runoff samples taken every 2 min. Time to fill 8 l buckets was recorded and the buckets were weighed immediately to obtain the runoff rate.

After the run, saturated alum solution was added to the buckets to flocculate the suspended sediment. After settling overnight, the excess water was poured out of the buckets and the sediment was transferred into 1 l bottles. The bottles were placed in ovens at 105°C for at least 24 h or until the sediment samples were dried. Dry weights were then taken to calculate the sediment delivery rates.

Following the run, the soil bed was drained and dried with a fan. The bed surface topography was recorded to show the pattern of surface scour or rilling. After the soil surface was dried, gravels and coarse materials on the

surface were scraped off to prevent their accumulation on the surface. The soil bed was then turned by a shovel for additional drying and preparation for the next run.

RESULTS AND DISCUSSION

Bed morphology under infiltration conditions

Surface features of the soil bed after the runs with the water tube set to 10 cm below the soil surface were used to illustrate erosion processes under infiltrating conditions. Before the experiment, it was hypothesized that the soil surface would form rills under added inflow conditions regardless of the hydrological conditions of the test bed. This was not always the case, especially under infiltrating conditions. Instead of forming rills, knickpoints were formed randomly throughout the bed. In several cases, these knickpoints developed into scallop-shaped depressions and crescents, similar to those described by Bryan (1990).

At 10 per cent slope, the crescent-shaped pits eroded headward until they coalesced with the next crescent-shaped pit upslope. Over time this process led to the development of shallow rills as the flow became concentrated in these areas where the crescent-shaped pits coalesced into one another. Insufficient run time may have prevented this from happening under the –10 cm drainage condition but the process became evident when the water tube was raised to the surface of the soil. When the water surface was set to the soil surface level, the bed changed from the mechanism of developing crescent-shaped pits to the development of headcuts. This occurred at a flow rate of about 22·7 l min^{-1} as the soil eroded into seepage conditions which enhanced detachment and the increased inflow provided extra transport for the development of rills. Rilling processes increased as both positive pore pressure and inflow were increased.

Bed morphology under seepage conditions

The bed surface after runs at 10 per cent slope and the water tube set at 10 cm above the soil surface was used to show the effects of seepage conditions on processes of erosion. Headcuts started in the general vicinity of the baffle plate installed 1·2 m from the exit end of the bed. The plate was placed so the effect of the seepage would not be influenced by the plot end effects. During the run, intense rilling took place and large aggregates of sediment were carried down the slope. In some instances, extensive collapsing of the sidewalls and rapid headcut advancement showed severe rill erosion in action. The stochastic nature of sidewall sloughing contributed to the high variability in sediment data under high flow rates.

The largest observable difference after the runs with seepage was caused by the slope steepness. After runs at 5 per cent slope, the bed surface had wide, shallow, meandering rills which resembled miniature rivers. There were several areas of cutting and deposition within the meanders after runs at 5 per cent slope. Under 10 per cent slopes, rills were incised much deeper and meandered less. The runs with 10 per cent slope appeared to be dominated by detachment and transport with very little deposition except the immediate area above the plot end.

Runoff and sediment delivery

The trends of sediment data were presented by plotting original data from all replicate runs as functions of either run time during the rainfall-only period or runoff for periods of added inflow. Figures 4 and 5 show runoff and sediment delivery rates for the first 30 min (rainfall-only portion) of the run. From the conceptual model in Figure 1, these graphs illustrated the water runoff and soil loss values typical for a 5 m segment on different positions along a hillslope. Hydrologic conditions for the summit, shoulder and upper backslope were mostly drainage dominant and represented in this study by the water tubes set at either –10 cm (–10WT) or disconnected (NWT). The water tube heights of 20 cm to 0 cm were designed to simulate runoff and erosion that may occur in interrill areas susceptible to seepage. The seepage condition simulated the hydrology on the middle to lower backslopes and footslopes in the landscape (Figure 1). Figures 4 and 5 both show an increased runoff and a higher soil loss rate when the bed was subjected to seepage conditions. The increased runoff was the direct result of background seepage flow when the water tube height was set above the soil surface. Two reasons may have caused the increased sediment delivery. Firstly, the soil's resistance to detachment may have

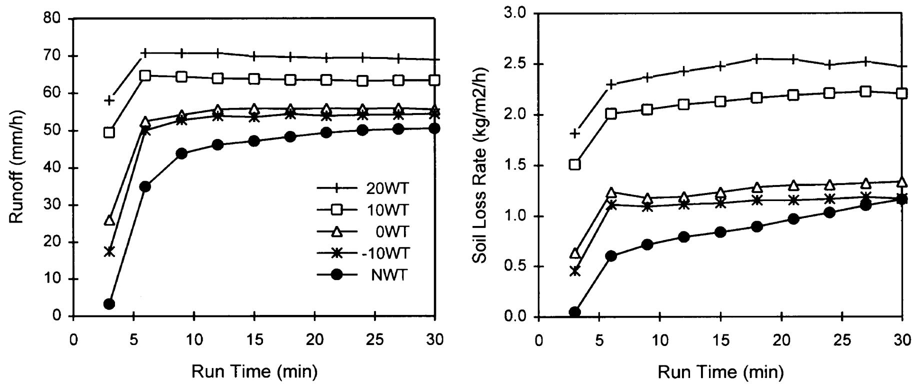


Figure 4. Average runoff and sediment delivery from the 50 mm h^{-1} rainfall event at 5 per cent slope

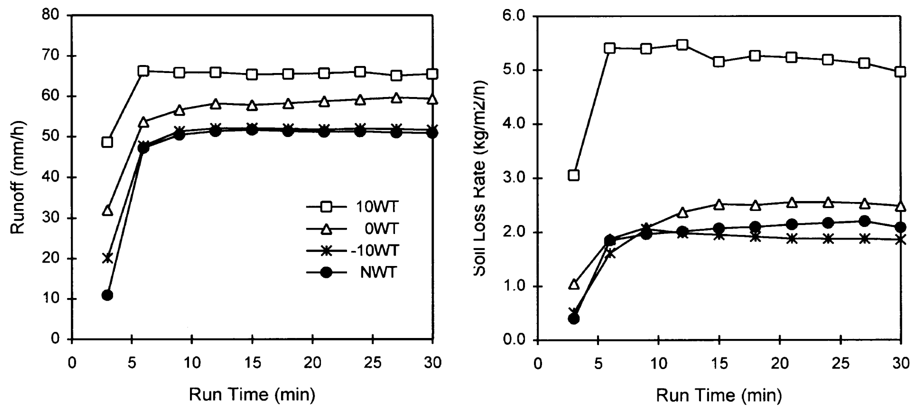


Figure 5. Average runoff and sediment delivery from the 50 mm h^{-1} rainfall event at 10 per cent slope

been reduced by the seepage force. Additionally, the increased sediment delivery under seepage conditions also could have been caused by the increased transport from the added exfiltration water. Either way, results showed that seepage conditions caused up to twice the soil loss rate under simulated rainfall.

Figure 6 depicts soil loss rates as functions of runoff at 5 per cent slope. Because of the data scatter, trend lines were drawn to illustrate the data trend. Sediment delivery rates at the lowest runoff value were those from the rainfall-only period of the run and all other higher runoff values were results from combined rainfall and added inflow. One surprising feature of this graph is that sediment loss rates were significantly lower under –10WT treatment than under free drainage conditions. Before the experiment, it was postulated that the soil loss rate would decrease as the level of the water supply tube was lowered from 20 cm above the soil surface to the free drainage condition. Therefore, for the two drainage situations, one would also think that the free drainage condition would have less soil loss than the condition with –10 cm water level. One explanation is that the capillarity caused a direct hydraulic connection from the surface to the water surface at 10 cm depth, which enhanced the drainage flux and subsequently, produced a greater suction on the soil aggregates, thus increasing the soil strength.

Figure 6 also shows a wide range of differences in soil erosion as the near-surface hydraulic gradient was reversed from exfiltration to infiltration conditions. There appear to be two different trends in this graph. The two drainage conditions, –10WT and NWT, seem to be approaching sediment detachment limiting regime as the flow transport is increased. However, under seepage conditions, especially under the 20WT treatment, there seems to be a linear association between water runoff and sediment loss. This indicates that at the 20 cm water tube conditions, soil loss rate will increase proportionally to the increase in inflow transport, indicating a transport-dominated sediment regime. This graph also shows an increased scatter in the sediment data at high

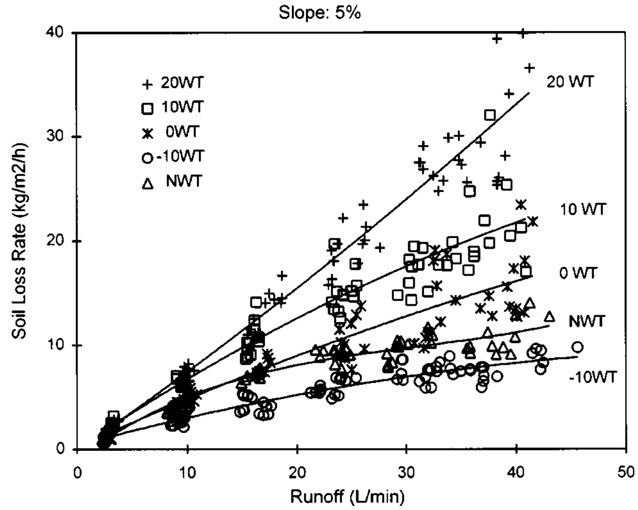


Figure 6. Soil loss rates as functions of runoff at different water tube heights for 5 per cent slope

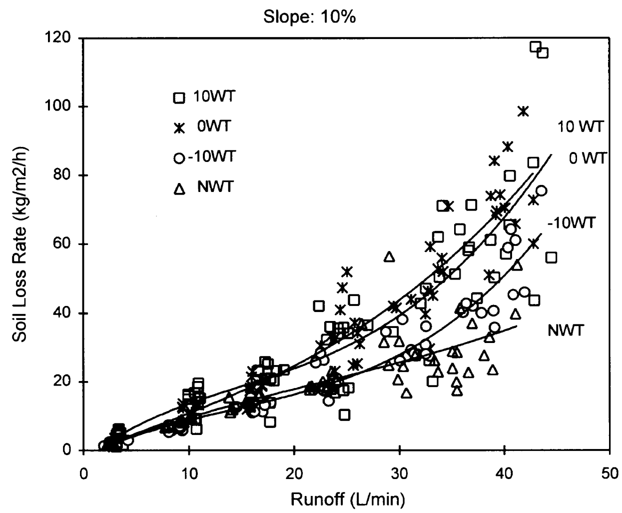


Figure 7. Soil loss rates as functions of runoff at different water tube heights for 10 per cent slope

sediment and runoff conditions. This high variability reflects the inherent nature of the chaotic processes that took place while the soil bed was under severe rilling. Headcutting, sidewall collapse, soil anomalies and variability in inflow all led to higher variability of the results under flow conditions.

Sediment loss rates at the 10 per cent slope, with trend lines drawn to show the data trend, are plotted in Figure 7. One feature different from results presented in Figure 6 for the 5 per cent slope is the less significant differentiation as the near-surface hydraulic gradient was shifted from seepage to drainage conditions. This shows that the effects of surface condition on soil erodibility, as demonstrated for the 5 per cent slope condition, will be masked as the slope gradient is increased. This figure also illustrates what happened when the soil surface was shifted from drainage to seepage conditions during the run with the –10WT treatment. Soil loss rates were similar for both –10WT and NWT treatments at low inflow/runoff rates until the $30{\cdot}31\,\mathrm{l\,min^{-1}}$ flow rate was introduced. At that point, the trend for the –10WT treatment changed and began to parallel that of the seepage treatments. This indicated that erosion processes must have changed. During the experiment, it was witnessed that this was the approximate time when the bed began to rill.

Table I. Average soil loss rate and sediment concentration at 5 per cent slope

Tube height (cm)	Soil loss rate ($kg\,m^{-2}\,h^{-1}$)						Sediment concentration ($g\,l^{-1}$)					
	Rain only	Rain with added inflow ($l\,min^{-1}$)					Rain only	Rain with added inflow ($l\,min^{-1}$)				
		7·6	15·1	22·7	30·2	37·8		7·6	15·1	22·7	30·2	37·8
20	2·5a*	7·3a	13·0a	19·4a	27·3a	36·3a	34·1a	35·3a	36·5a	37·5a	39·2a	42·1a
	(0·4)†	(0·7)	(2·0)	(2·1)	(1·5)	(10·6)	(5·1)	(3·4)	(3·4)	(3·3)	(2·9)	(8·7)
10	2·2a	6·3b	10·5b	15·1b	17·3b	21·3b	33·0a	32·0b	31·9a	30·1b	26·7b	27·5b
	(0·3)	(0·3)	(1·5)	(1·5)	(1·5)	(3·0)	(3·0)	(0·6)	(3·9)	(2·9)	(1·8)	(4·3)
0	1·3b	4·9c	8·5bc	10·4c	13·0c	15·8bc	22·5b	24·1c	24·8b	20·6c	20·1c	19·5c
	(0·4)	(0·4)	(1·6)	(1·8)	(4·0)	(3·6)	(6·8)	(1·7)	(5·0)	(3·2)	(5·3)	(3·8)
–10	1·1b	3·1e	5·0d	6·9d	7·7d	8·3c	20·5b	16·7d	15·2c	13·6d	11·5d	10·2d
	(0·3)	(0·6)	(0·5)	(0·4)	(0·3)	(0·8)	(3·8)	(2·4)	(2·1)	(0·4)	(0·5)	(0·6)
none	0·9b	4·0d	7·2c	9·1c	9·7cd	10·7c	18·6b	22·6c	21·9b	18·9c	16·1cd	13·6cd
	(0·2)	(0·4)	(0·4)	(0·4)	(1·2)	(1·7)	(3·6)	(1·5)	(0·6)	(1·5)	(1·4)	(1·6)

* Differences are significant at $P = 0{\cdot}05$ if followed by different letters within each column
† The numbers in parentheses are standard deviations

Table II. Average soil loss rate and sediment concentration at 10 per cent slope

Tube height (cm)	Soil loss rate ($kg\,m^{-2}\,h^{-1}$)						Sediment concentration ($g\,l^{-1}$)					
	Rain only	Rain with added inflow ($l\,min^{-1}$)					Rain only	Rain with added inflow ($l\,min^{-1}$)				
		7·6	15·1	22·7	30·2	37·8		7·6	15·1	22·7	30·2	37·8
10	5·3a*	16·1a	22·4a	36·2a	56·8a	67·8a	79·9a	75·8a	64·4a	73·8a	81·6a	81·0a
	(0·6)†	(1·5)	(1·6)	(3·1)	(6·8)	(25·5)	(15·3)	(8·6)	(7·4)	(8·6)	(14·5)	(24·3)
0	3·4b	11·2b	18·2b	34·4a	48·3a	73·1a	54·5b	52·8b	53·0b	64·8a	68·5a	81·9a
	(0·2)	(2·5)	(3·0)	(9·3)	(7·5)	(9·5)	(1·2)	(10·2)	(7·6)	(16·6)	(8·4)	(10·6)
–10	2·0b	6·2c	12·9c	20·5b	30·2b	49·4b	37·0c	35·6c	38·7d	41·4b	46·0b	58·4ab
	(0·3)	(1·2)	(1·4)	(4·5)	(1·8)	(10·8)	(4·8)	(5·6)	(4·7)	(7·2)	(3·1)	(9·6)
none	2·1b	8·3c	13·7c	19·3b	28·8b	30·4c	39·3c	43·2bc	42·9c	40·2b	45·3b	38·9b
	(0·2)	(1·1)	(1·8)	(0·9)	(8·7)	(10·2)	(3·5)	(2·1)	(4·2)	(1·4)	(15·9)	(10·7)

* Differences are significant at $P = 0{\cdot}05$ if followed by different letters within each column
† The numbers in parentheses are standard deviations

Under seepage conditions at 10 per cent slope, the difference between the soil loss rates from the 0WT and 10WT treatments became insignificant. This is probably because once the rilling was initiated, the bottom of the rill changed to seepage conditions and the high flow transport capacity associated with the greater slope overshadowed the minute difference in the exfiltration gradient. At this point, the erodibility of the soil was greatest because the soil eroded as fast as it could be transported. Intense rilling, sloughing of rill channels, and rapid rill head advancement were also witnessed.

Sediment data analysis

A comparison of the means was conducted so that trends could be deduced to aid in the analysis of the raw data figures. Mean values for each replicate run were derived from averaging the last four samples for rainfall-only and the last three samples for the rainfall with added inflow portion of the run. The Student–Newman–Keuls method was used to see if the means were significantly different among different hydrologic treatments. Table I contains the average soil loss and sediment concentration values and their statistical attributes for conditions under 5 per cent slope. Results for 10 per cent slope treatment are presented in Table II.

In general, soil loss was reduced as the near-surface hydraulic gradient was lowered from exfiltration to infiltration conditions. It also showed the effect of applying a small suction (–10WT) on reducing overall soil loss. This indicates that the soil particles were held in place more when they were put under tension than if the soil was allowed to free-drain. At 10 per cent slope, the effect of assisted drainage on reducing soil loss was lost at high inflow rates. If analysed closely, different phases of sediment detachment and transport interaction can

Table III. Slope effects, expressed as the ratio of measurements from 10 per cent slope to those from 5 per cent, for different hydraulic gradients

Tube height (cm)	Sediment delivery						Sediment concentration					
	Rain only	Rain with added inflow ($l\,min^{-1}$)					Rain only	Rain with added inflow ($l\,min^{-1}$)				
		7·6	15·1	22·7	30·2	37·8		7·6	15·1	22·7	30·2	37·8
10	2·44	2·55	2·13	2·40	3·29	3·19	2·42	2·37	2·02	2·45	3·05	2·95
0	2·65	2·28	2·14	3·31	3·66	4·62	2·42	2·20	2·13	3·15	3·41	4·19
–10	1·86	1·96	2·58	2·97	3·95	5·94	1·80	2·13	2·55	3·04	3·99	5·73
none	2·29	2·07	1·89	2·13	2·95	2·84	2·12	1·91	1·96	2·13	2·82	2·86

probably be deduced from the 10 per cent slope, –10WT treatment. From rainfall-only through the 7·6 $l\,min^{-1}$ inflow rate, limited flow and drainage conditions restricted the soil's ability to detach and transport. From 7·6 to 30·3 $l\,min^{-1}$ flow, the bed changed from drainage to seepage, but the bed was still detachment-limiting but not transport-limiting because sediment loss increased but sediment concentration was comparable to free-drainage conditions. At the greater flow rates, detachment was no longer limiting since the soil had been eroded down to the saturated zone within the bed and the drainage condition was reversed to the seepage condition.

The association of separate sediment detachment and transport regimes to drainage and seepage gradients was further illustrated by trends in the sediment concentration data. Under drainage conditions at 5 per cent slope, the sediment concentrations were decreased despite an increase in soil loss as the flow rate was increased. This indicates that sediment supply was limiting despite the increased flow detachment and transport potentials. Under seepage conditions, sediment concentrations remained somewhat constant, indicating a direct linkage between sediment detachment and transport processes. As the slope steepness was increased to 10 per cent, sediment concentrations showed different trends. The limiting effects of detachment and transport at low slopes were overcome as the hydrologic condition of the soil may have been changed during the run because of the much greater rates of soil loss. Rapid increases in sediment concentration at high flow rates observed at 10 per cent slope under 0WT and –10WT treatments were attributed to the increased seepage gradient in the rills as the soil was eroded down.

Slope effects

To further quantify the slope effects, we calculated soil loss and sediment concentration ratios between those obtained under 10 per cent and 5 per cent slopes and present the results in Table III. As discussed earlier, the largest increase in soil loss rate occurred at the –10WT treatment because at 10 per cent slope the soil eroded enough that it underwent seepage conditions.

By viewing the change in the soil loss rate under rainfall conditions, the increase in soil loss was due mainly to an increase in transport capacity provided by the steeper slope. However, during flow conditions, an increase in slope steepness increased both the transportability and detachability of the flow. Also during flow conditions, an increase in soil loss and sediment concentration ratios was observed for the different hydrologic conditions. This occurred at or following the initiation of the rilling process for the 10 per cent slope treatment. This can be readily seen at the –10WT treatment. Like the freely drained condition, the slope factor for the rainfall and lower flow rates yield relatively constant soil loss and sediment concentration ratios. This shows that the increase in soil erosion was caused by an increase in transportability of the sediment at the steeper slope. At the greater flow rates, the rate of erosion was greatly increased because of the combined effects of the steeper slope and increased seepage pressure. This illustrates how the combination of slope and hydraulic gradient can affect the erodibility of the soil.

CONCLUDING REMARKS

This study examined the effects that different hydraulic gradients, especially seepage and drainage that can occur at different positions on a hillslope, can have on the dominant erosion processes that occurred throughout. Different slope and hydrological conditions were used to simulate sections of a hillslope. Results showed that,

under drainage conditions, rilling is limited and the surface contained scattered crescent-shaped pits after the run. Under seepage conditions, rilling started during the rainfall-only portion of the run and the subsequent inflows introduced at the top of the soil pan further accelerated the headward erosion of the rills.

In the landscape scale, erosion from the summit or upper backslope areas was simulated by drainage condition under the rainfall-only portion of the run. As the location on the landscape moves downslope, the surface flow was increased and the dominant hydrologic condition may also shift from drainage to seepage situations. If the 5 m soil box represents the condition of a hillslope segment in the landscape, erosion rates would vary as much as 60 to 70 times as location moves downslope in uniform soil. This indicates that rills and gullies on lower levels of the backslope may be catalysed by seepage conditions rather than hydraulic flow shear stress alone as used in many erosion prediction models.

More research is needed to model seepage and hydraulic gradients through different soil textures and other subsurface hydrological conditions. Though we know that seepage faces exist in natural landscapes, little knowledge exists about the frequency and factors needed to predict the likelihood of the seepage faces throughout the year. This would be necessary if new erosion prediction models want to accurately model hydrologic processes at the landscape scale. This, along with an understanding of spatial and temporal factors that affect hydrologic gradients, will be needed so that lateral subsurface flow and exfiltrating water can be included in erosion process models.

Current farming practices need to be evaluated for their effects on hillslope hydrology, which may alternatively impact runoff, erosion and sediment production. Further study may result in different management practices and erosion control strategies in regions where seepage may occur, such as using drainage as an erosion control measure.

REFERENCES

Birkeland, P. W. 1984. *Soils and Geomorphology,* Oxford University Press, New York, 372 pp.

Bryan, R. B. 1990. 'Knickpoint evolution in rillwash', *Catena Supplement,* **17**, 111–132.

Bunting, B. T. 1961. 'The role of seepage moisture in soil formation, slope development, and stream initiation', *American Journal of Science*, **259**, 503–518.

Dunne, T. 1990. 'Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow', *Geological Society of America Special Paper*, **252**, 1–28.

Foster, G. R., Eppert, F. P. and Meyer, L. D. 1979. 'A programmable rainfall simulator for field plots', *Proceedings of Rainfall Simulator Workshop,* 7–9 March 1979, Tucson, Arizona, US Department of Agriculture, Science and Education Administration, Agricultural Reviews and Manuals, **ARM-W-10**, 45–59.

Howard, A. D. and McLane, C. F. 1988. 'Erosion of cohesionless sediment by groundwater seepage', *Water Resources Research,* **24**, 1659–1674.

Huang, C. and Laflen, J. M. 1996. 'Seepage and soil erosion for clay loam soil', *Soil Science Society of America Journal,* **60**, 408–416.

Iverson, R. M. and Major, J. J. 1986. 'Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization', *Water Resources Research,* **22**, 1543–1548.

Kirkby, M. J. and Chorley, R. J. 1967. 'Throughflow, overland flow and erosion', *Bulletin of the International Association of Scientific Hydrology,* **12**, 5–21.

Neibling, H. W., Foster, G. R., Nattermann, R. A., Nowlin, J. D. and Holbert, P. V. 1981. 'Laboratory and field testing of a programmable plot-size rainfall simulator', in *Erosion and Sediment Transport Measurement,* Proceedings of the Florence Symposium, June 1981, International Association of Hydrological Sciences, Publication No. **133**.

Ritter, D. F., Kochel, R. C. and Miller, J. R. 1995. *Process Geomorphology,* W. C. Brown Publishers, Dubuque, Iowa, 546 pp.

Stolte, W. J., Rudra, R. P. and Dickinson, W. T. 1990. 'The impact of seepage on soil erosion', *Transactions of American Society of Agricultural Engineers,* **33**, 475–479.

Terzaghi, K. and Peck, R. B. 1967. *Soil Mechanics in Engineering Practice,* John Wiley and Sons, New York, 729 pp.